AD-A140 081 DEVELOPMENT OF AN INTERFEROMETRIC TECHNIQUE FOR REDUCTION OF BACKGROUND RADIATION AT 10 MICROMETERS(U) ARIZONA UNIV TUCSON DEPT OF PHYSICS 1984 1/1

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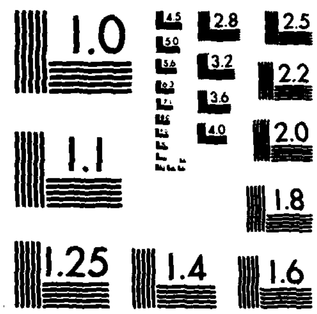

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

THE UNIVERSITY OF [redacted]

TUCSON, ARIZONA 85721 USA

COLLEGE OF ARTS AND SCIENCES

FACULTY OF SCIENCE
DEPARTMENT OF PHYSICS
BUILDING #81

1984

1. Introduction

This report concerns the final status of the ONR contract ~~no. N00014-81-C-0794~~, entitled "Development of an Interferometric Technique for Reduction of Background Radiation at 10 μm."

The purpose of the proposed instrument was to improve the detectability of a background limited source in the atmospheric "window" from 8 to 12 μm. Such an improvement would be possible if the photons arising from the source and background could be discriminated interferometrically such that the "desired" signal photons were preferentially detected. This has been the motivating idea of the devices considered.

A great deal of progress toward fulfilling the particular design requirements of the proposed instrument has been made, and this is the subject of Section 2. However, in the process of calculating the instrument performance by computer modeling, an unexpected problem was uncovered (see Section 3.5 for a detailed description). Variations of the parameters involved have not succeeded in circumventing the problem. Unfortunately, the consequence of this problem is that improvement in the signal to noise ratio is not attainable with this instrument.

Further study covered a wide spectrum of alternative methods of achieving our initial goals. In the formal analysis of all designs considered, it became apparent that no improvement in the ratio of detected signal photons to detected background photons could to be expected using interferometric reduction. Section 2.6 presents an explanation of the inability to detect signal photons preferentially over background photons. This argument is quite general and can be applied to any of the designs considered.

However, one of the ideas considered was found to have merit in certain classes of background limited detection. This mode of operation will detect signal and background photons alike and, therefore, the statistical fluctuations of the background will still limit the signal to noise ratio. The salient feature of this device is the ability to measure and subtract an extended, nonuniform background intensity from an unresolved (or point-like) signal intensity. The usual technique must measure the background beyond the source and extrapolate and/or interpolate to the region occupied by the desired signal.

This method of background compensation is fundamentally different from the originally proposed technique. Since the original method would have relied on interferometric cancellation of the background field, it shall be referred to as "background amplitude compensation." The new device uses interferometric techniques to measure the background in the line of sight and then subtracts the background from the signal after detection of the field has occurred. This latter technique will therefore be called "background intensity compensation."

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Although the original proposal did not address background intensity compensation, approval for further study of this technique was granted at the time of the last extension. A description of the theory of operation and results of testing of this technique at a wavelength of 6328 A are provided in Section 3.

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2. Background Amplitude Compensation

This section shall deal with the various design aspects of the originally proposed device. The subsections which follow are in roughly chronological order, although some projects were carried out simultaneously.

2.1. Regular Array Grating

The instrument design considered at the start of the contract period is depicted in Figure 1. A problem with the intended grating was discovered shortly before the start of the contract period. In the mask plane behind the regular array phase grating, the peaks for the distribution of the desired signal and background amplitudes were found to occupy the same region, i.e., the region where the background amplitude was to be blocked. Previous tests with 3 mm microwaves did not measure the signal while the background blocking mask was in place, and this problem went undiscovered until the signal diffraction pattern in this plane was calculated analytically. Further tests with the 3 mm microwave equipment confirmed the results of this analysis.

2.2. Irregular Array Grating

Alternatives to the initial design were considered when the problem described in Section 2.1 was realized. It was found that, by permitting some of the grating elements to be twice as wide as normal, the peaks of the background and signal diffraction patterns in the mask plane were very thoroughly separated. In this case, the signal refers to that part of the image field which overlaps the double-width grating elements. An irregular grating of this sort can be extended into a two-dimensional array by forming a product of linear arrays. The grating pattern which was found best suited to the proposed application is shown in Figure 2. The light elements produce a phase shift of 180 degrees relative to the dark elements. This pattern provides for eight separate regions in the field where background compensation would occur.

2.3. 3 mm Microwave Tests

A plexiglass irregular array phase grating was constructed to test the idea presented in Section 2.2. A line grating was used rather than the two-dimensional grating in order to simplify construction and detector positioning. The irregular grating replaced the previous regular grating in the 3 mm microwave setup. Results of measurements in the mask plane were in good agreement with the numerical diffraction calculations as shown in Figure 3. Differences between the measured intensities and the theoretical values are attributable to the aberrations of the optical elements and the departure of the microwave source from an ideal point source.

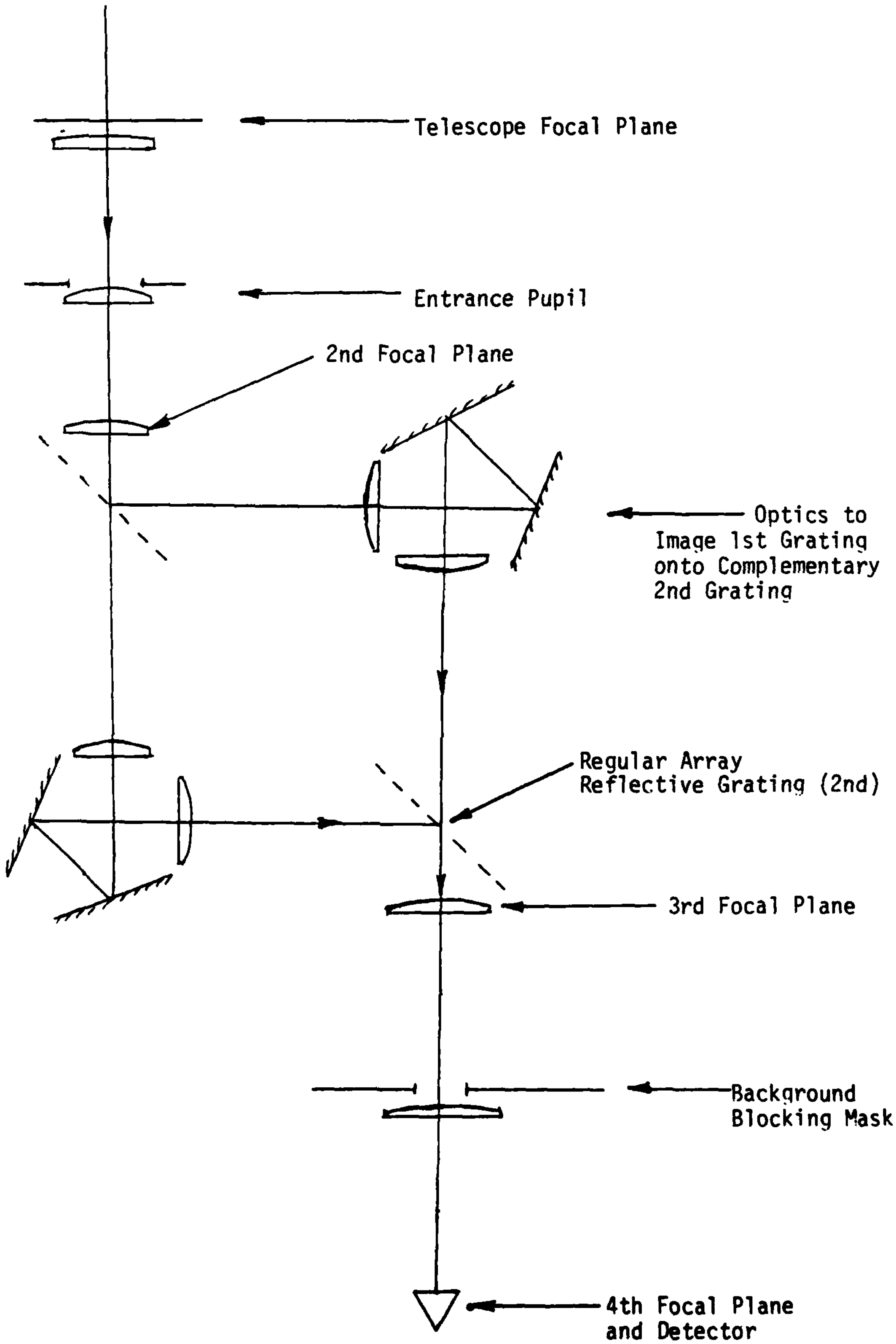


Figure 1 - Basic Design of Initially Proposed Instrument

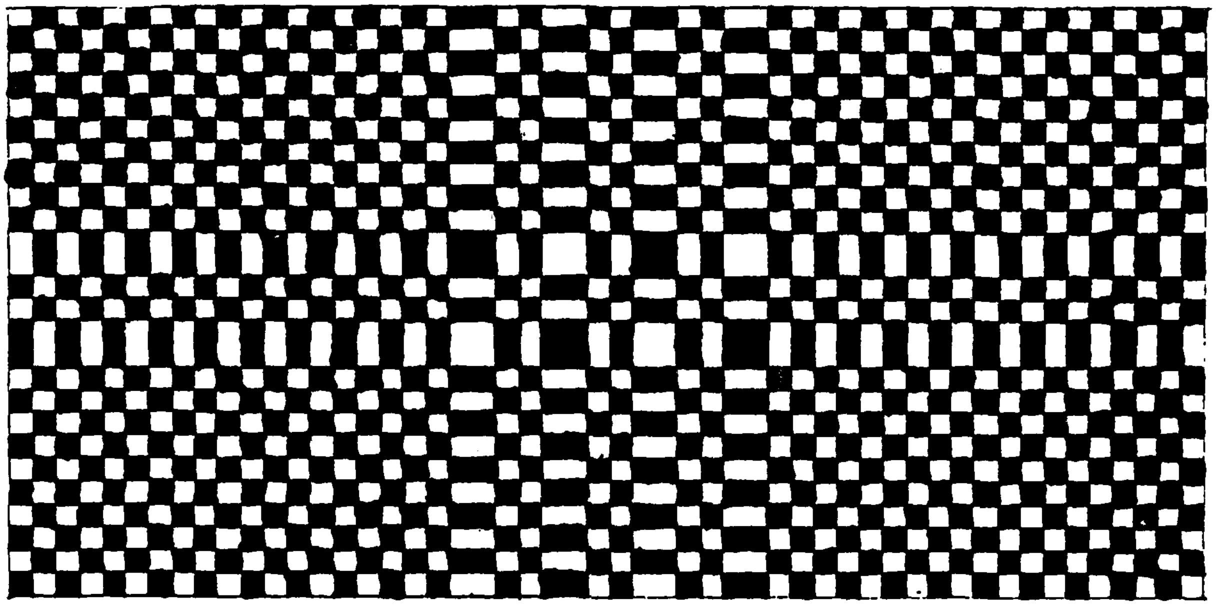
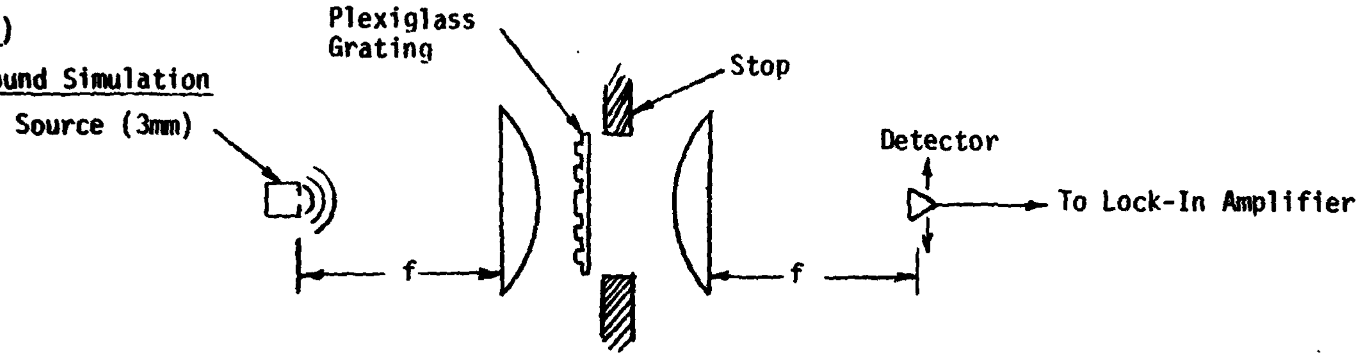


Figure 2 - Irregular Array Grating

The dark elements shift the phase of the transmitted wavefront by 180° relative to the light elements. The desired signal would be measured at the eight "double-size" squares in the central region.

Fig-3.a)

Background Simulation



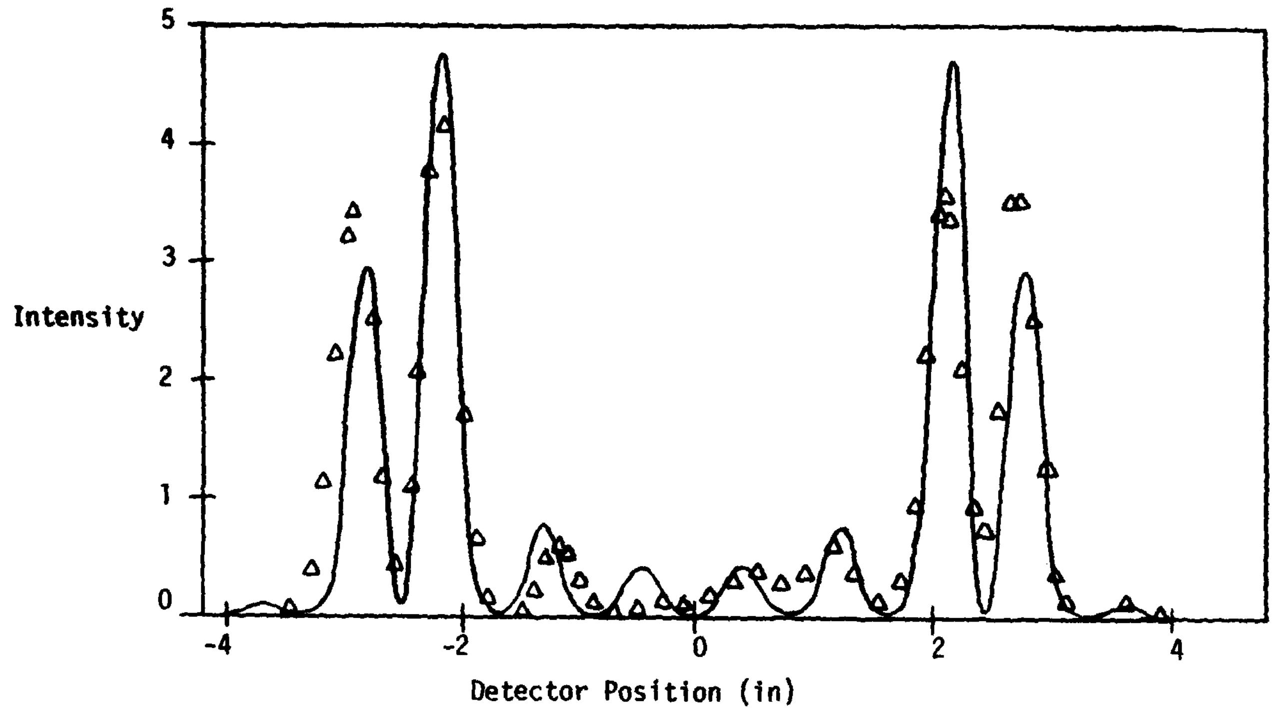
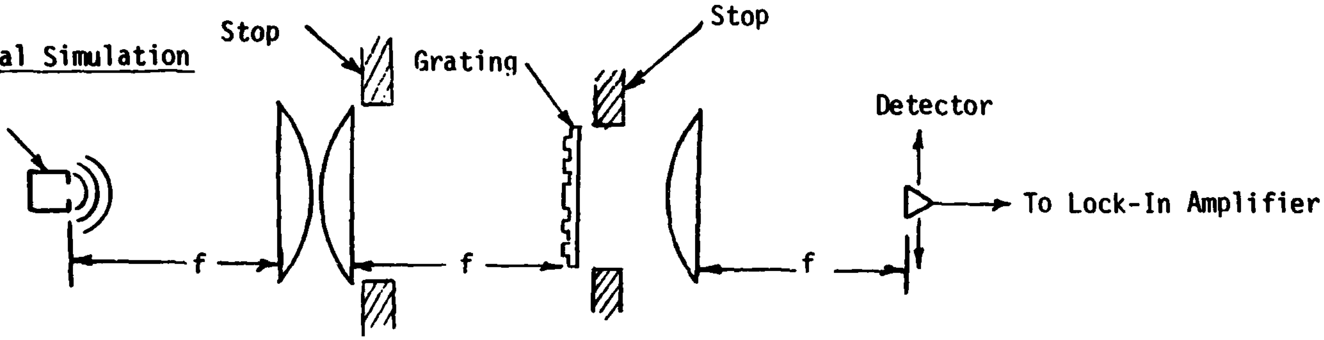


Figure 3 - Results of 3mm Microwave Tests

A plexiglass irregular array phase grating is used. The solid line curve is calculated numerically and the triangles represent data from the set-up shown above the plot.

Fig-3.b)

Desired Signal Simulation



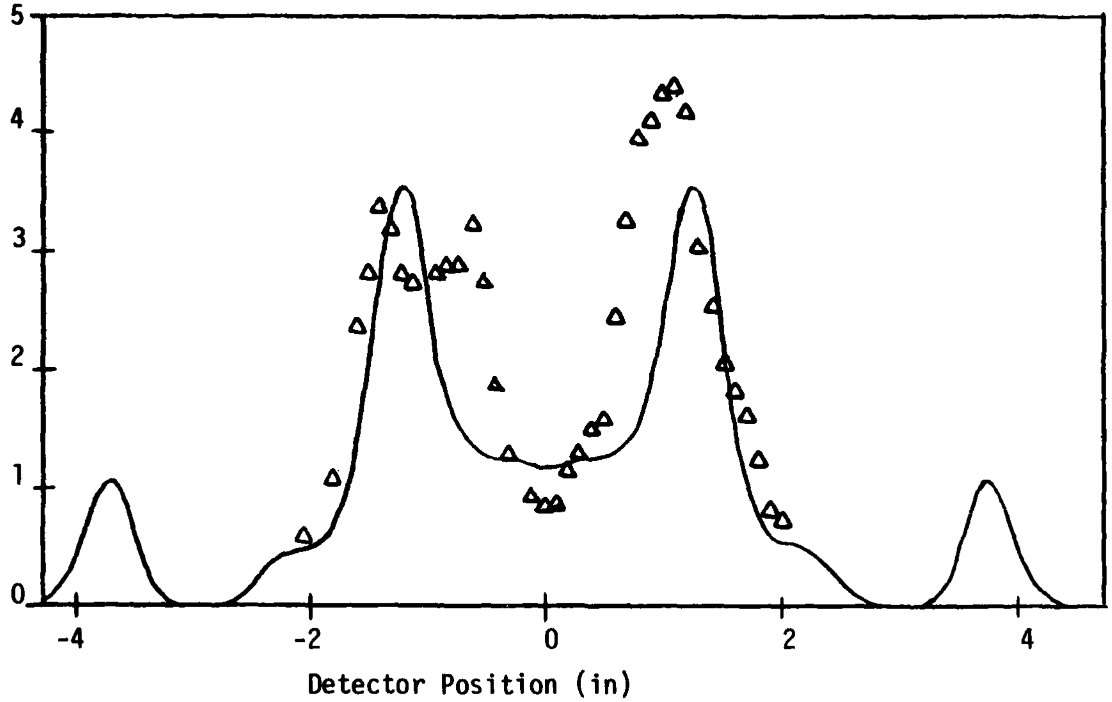


Figure 3 - (continued)

2.4. Optical Elements

Figure 4 gives a schematic layout of the planned optical design. For the sake of clarity, the figure does not show certain folding mirrors which would have been included to minimize the volume of the dewar required for low temperature operation. Except for the achromatic phase shifters, all transparent optical elements were to be made of germanium, which has the advantages of low absorption and a nearly constant refractive index within the 8 to 12 μm atmospheric window. Due to the unusually high index of refraction of germanium, ~ 4, the utility of the design is very dependent on antireflection coatings. Coatings were found to be commercially available which reduced the air-germanium reflection from 36% to < 1% in the full range of the atmospheric window.

2.4.1. Achromatic Phase Shifters

A crucial aspect of the instrument design was devising a means of producing a 180° phase shift between alternate grating elements over the full band of interest. A modified Mach-Zehnder interferometer with reflective gratings as beamsplitters was used to divide the image plane into two beams which could be phase shifted with respect to each other. This phase shift can be made nearly achromatic by inserting, into the two beams, a carefully selected combination of transparent plates made of different materials. Upon further study of this idea, it was found that a slight difference in the air path length between the two legs, coupled with a single plate, could produce an achromatic phase shift. Many materials were considered, with the optimum choice found to be cesium iodide (CsI). For a plate thickness of 596 μm and an air gap of 445 μm, the phase shift in the wavelength range of 8-14 μm varies from 176.9° to 183.1°. The sensitivity of the phase shift to a change in plate thickness was an important design consideration. In the case of CsI, a 10 μm error in the ideal plate thickness, with the air path difference adjusted to minimize the effect of the error, changes the phase variation from 6.2° to 6.8°. The use of this technique to provide an achromatic relative phase shift could be useful in a variety of interferometric systems.

2.4.2. Grating Imaging

In order for the Mach-Zehnder system to represent a simple phase grating adequately, it is essential that the elements of the first reflective grating be accurately mapped to the corresponding elements of the second grating. This requirement was found to impose much more stringent demands on the optics than was typical for the rest of the system.

Several designs were considered before one of sufficient quality was found. In order to evaluate a specific design, a computer ray tracing code (ACCOS-V) was used. Rays were initiated at representative points on the first grating, and then directed to cover the pupil uniformly. After the trace was carried out to the second grating surface, the spot diagrams resulting from these ray bundles could be analyzed.

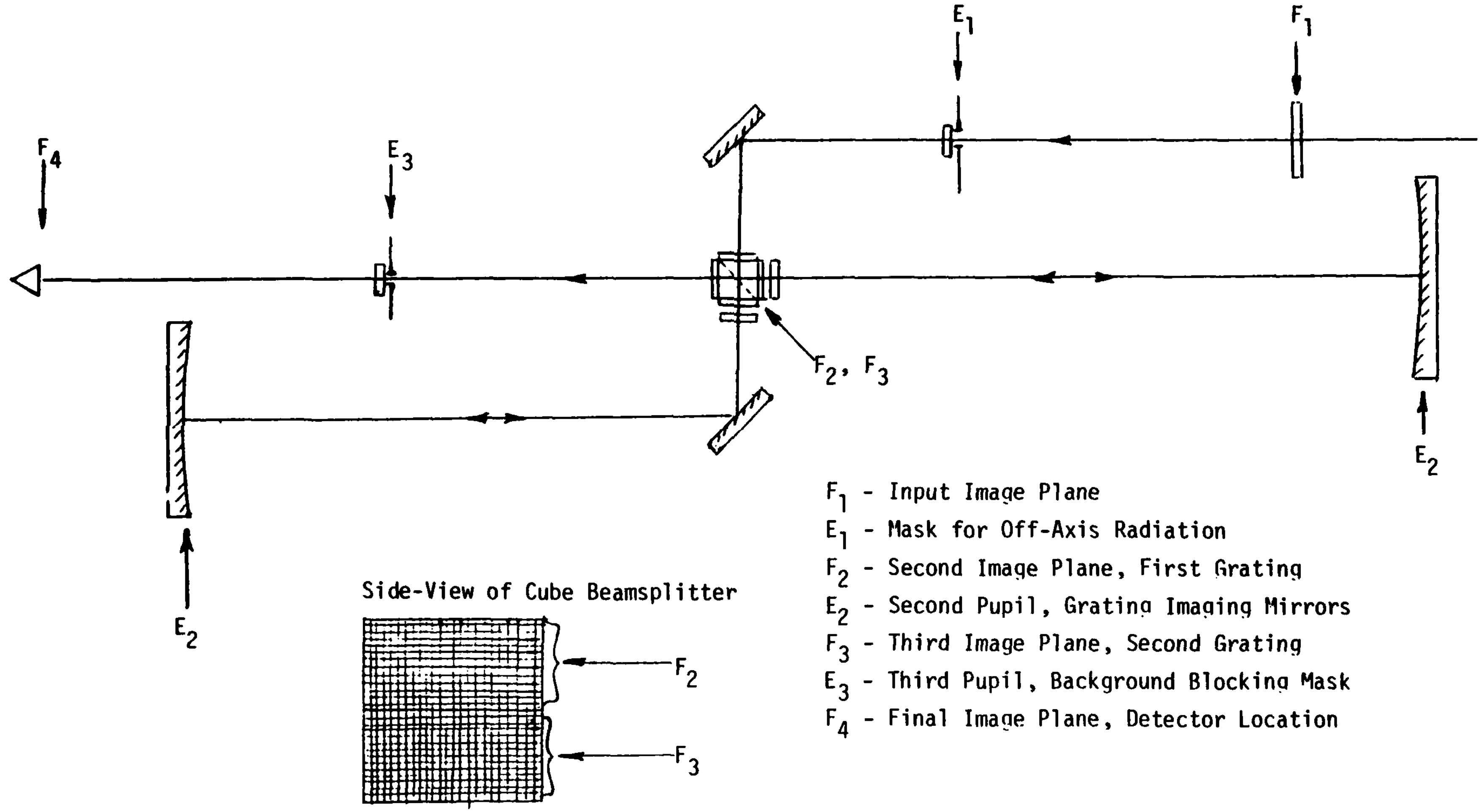


Figure 4 - Schematic Lay-Out of Background Amplitude Compensator

This illustrates the refined design of the initially proposed instrument. For the exception of the expanded side-view, the scale is 1/2 .

The design which gave the best imaging properties was also quite simple (see Figure 4). The two reflective gratings lie in the same physical plane of a cube germanium beamsplitter. Although the gratings are tipped at 45° relative to the optical axis, the effect of the germanium prism is to reimage this surface to an angle of only 12°. This considerably reduces the aberration near the edges of the imaging field. Plano convex germanium field lenses which are in optical contact with the cube beamsplitter image the objective onto the spherical mirrors (at E2). The two plates in these two divided beams are the CsI phase shifters. Although only one plate is required in principle, two were to be used in order to balance the reflective losses of the two legs and to allow for thicker plates. The difference in the thickness of the two plates must equal the thickness of the single plate described in Section 2.4.1. Note that, since the gratings lie next to each other, they are rectangular in order to minimize the object and image separation. For the arrangement shown, the r.m.s. spot diameter from the geometric ray trace calculations varies from 13 to 35 μm across the full field of the grating. This is quite acceptable, considering that the diffraction-limited spot size at a 10 μm wavelength is 35 μm for this f/3.5 system. The combined effects of diffraction and aberration are, therefore, expected to produce an upper limit spot size of ~ 50 μm, acceptably small compared to the grating element size of 450 μm.

2.5. Computer Modeling

Soon after the idea for the irregular grating was proposed, the diffraction patterns due to both signal and background sources were calculated numerically. The plane in which this diffracted amplitude was initially evaluated was located at the background blocking mask (E3 in Figure 4). It seemed clear at this point that, since the peak amplitude due to the signal did not overlap the peak due to the background, the signal to noise level after this mask plane would be improved. Extending the numerical calculations to the final image plane was to be the test of this expectation. The necessary calculations turned out to be quite tedious, and a considerable amount of time and effort was spent before the model results were reliable. Unfortunately, the outcome did not confirm the intuitive reasoning presented above.

To simulate a uniform background, fifty randomly distributed point sources were placed in the plane of the objective. The signal source was simulated by a plane wave at the objective which could be tipped at any desired angle. The resultant amplitudes were calculated in the final image plane with the blocking mask both in place and absent. The background distribution was quite uniform in this plane when the blocking mask was removed. However, when the blocking mask was in place, the final image plane distribution became peaked at the eight locations where the double-size grating elements were imaged, corresponding to the intended signal regions. To the expected precision of the calculation, no increase in the signal to background ratio was found upon putting the blocking mask in place.

The effect of changing parameters in the grating and mask was assessed next. By making the grating larger, with a greater number of small elements on the periphery, the background distribution in the mask plane became more sharply peaked. However, the amplitude level which is not masked still led to peaks of the same size in the final image plane. If the mask was designed to block off more background, the peaks in the final image plane resulting from both the signal and background became wider (as expected from the smaller mask aperture), but their amplitude ratio remained unchanged.

2.6. Inability to Distinguish Background and Signal Photons

A variety of alternate designs, aimed at achieving the initial goals of the contract, were considered. In all cases, the background photons were eliminated by the same factor as were the signal photons, with no gain in the signal to noise ratio. This section gives a general explanation for this result.

Huygen's principle states that every point of an arbitrary electromagnetic wavefront can be regarded as the origin of a point source, and the superposition of all these point sources is, in all respects, equivalent to the original wavefront. In addition, from the principle of superposition, the amplitude of an electromagnetic wave at a chosen point in space will equal the sum of amplitudes arising from all point sources representing the wave. The point sources which represent the wave can be selected on any wavefront and, therefore, are not restricted to any spatial region as the original point source may have been.

Now consider a background amplitude compensator which is to be placed in front of an intensity detector D. We require this device to pass photons which originate at some point S preferentially over those which originate on a surface B which lies between S and D (see Figure 5). With this construction, any point b on B will intersect a point on the wavefront of a photon generated at S. Therefore, the amplitude due to this photon at D can be determined by considering separately the amplitude produced at D by every point on B. It follows that, if the compensator is to effect an overall reduction in amplitude at D for background sources at B, then the amplitude at D due to S must be reduced by the same factor. This contradicts the requirement we have set for this device.

The argument above applies to a point-like signal and is clearly a special case of the proposed instument, which was to operate on an extended field and compensate for more than just a surface of background sources. However, one arrives at the same conclusion by applying the argument to all points in the region of the signal and all surfaces in the region of the background.

It is important to note that the argument that has been presented is only as strong as the starting points: Huygen's principle and the principle of superposition. For sufficiently strong fields in a nonlinear medium, linear superposition will not be entirely correct. However, the practical applications for the type of instrument proposed

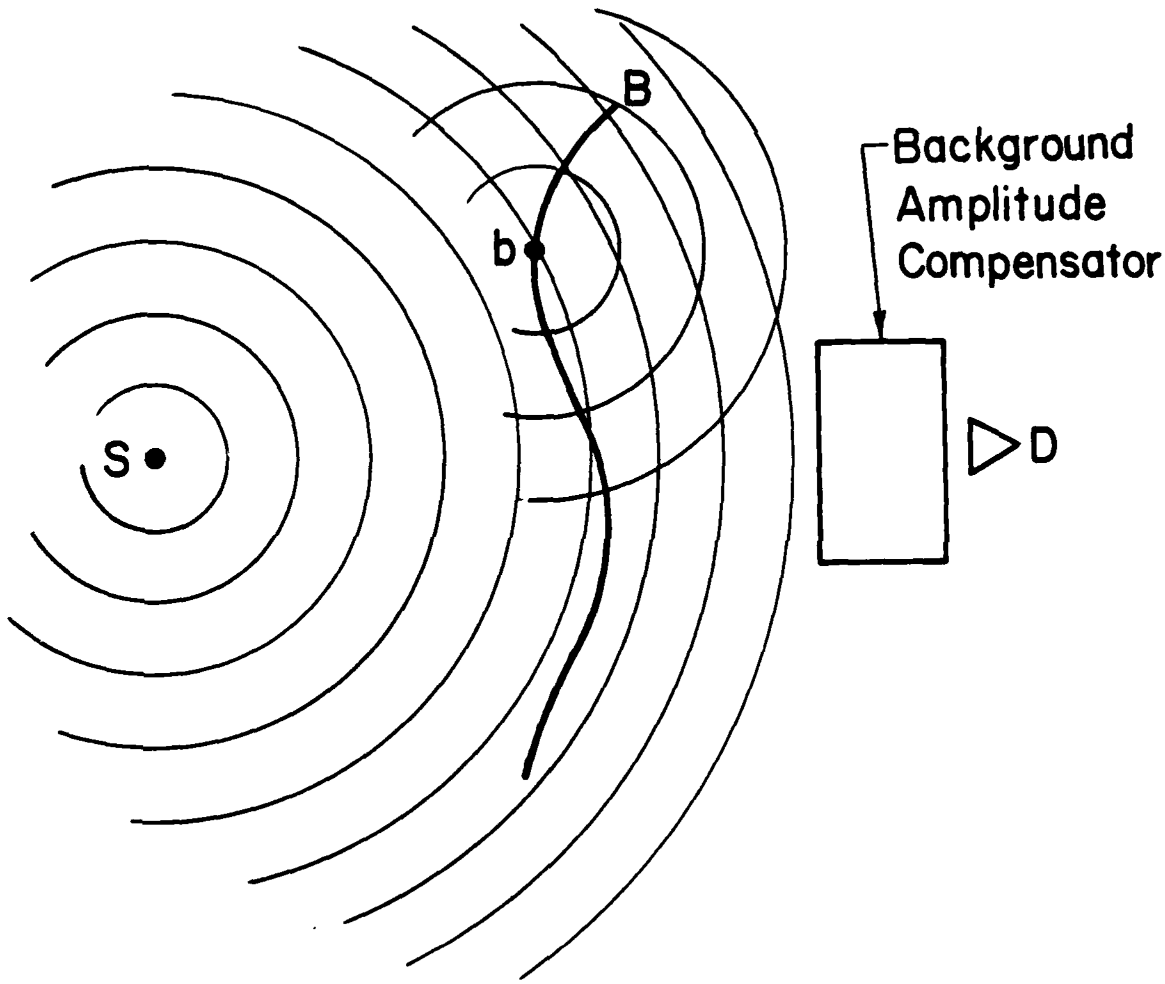


Figure 5 - General View of a Background Amplitude Compensator

would almost certainly be directed toward weak fields in highly l media. In the case of Huygen's principle there is more room for s lation. Although this concept is well accepted, it is not dir derivable from Maxwell's equations. The derivation of Fraunh Fresnel diffraction given by Born and Wolf (1959) makes use of Hu principle in a modified form which includes an "inclination fac This factor gives directional structure to each point making up a front. Such structure is not expected from any realistic backg source, and the equivalence of a physical source and a "Huygen's source" seems questionable.

The objections raised above should demonstrate that this is nc a fully closed subject. However, since no counterexample to the ment presented has been found, it does not seem reasonable to cor active study in this area.

Reference

M. Born and E. Wolf. 1959, "Principles of Optics," Pergamon Press.

3. Background Intensity Compensator

Among the alternate designs which were considered, one was found to have interesting features even though it did not satisfy the initial objective. It appeared that this device would be capable of distinguishing the detected intensities due to a point signal source and a nonuniform background. This idea was developed into a working model in the most recent extension period of this contract.

3.1. Principle of Operation

Figure 6 shows the basic optical design. The signal source is represented here by a plane wave tipped from the optical axis by an angle θ. The entrance wavefront is then sampled by two matched apertures which are separated by a distance S. Objectives at the apertures focus this plane wave onto detectors D1 and D2. Before the detectors, the beams are combined by a 50/50 beamsplitter at B. For ideal alignment of the system, the detector outputs will be:

$$d_1 = C \cos^2 \left(\frac{\pi\theta S}{\lambda} + \frac{\Delta}{2}\right)$$

and

$$d_2 = C \sin^2 \left(\frac{\pi\theta S}{\lambda} + \frac{\Delta}{2}\right) \quad ,$$

where C is a constant intensity, λ is the wavelength, and Δ is the phase difference of the optical paths from the first objective to D1 and from the second objective to D1. The difference between these detector outputs will clearly depend on Δ, and will have a maximum magnitude when the term in parentheses is an integral multiple of $\pi/2$. If a background source is close enough to the objectives to avoid overlap of the two beam wavefronts on the detectors, then no interference between the beams can result. The time-averaged detected intensity due to such sources must then be the same for both detectors. Departures of the difference between these intensities from zero can only result from statistical fluctuations.

3.2. 6328 Å Testing

Although the principle described in the previous section applies to the entire electromagnetic spectrum, the testing was conducted at an optical wavelength of 6328 Å. The primary reason for this choice was the availability of equipment designed for this wavelength. In

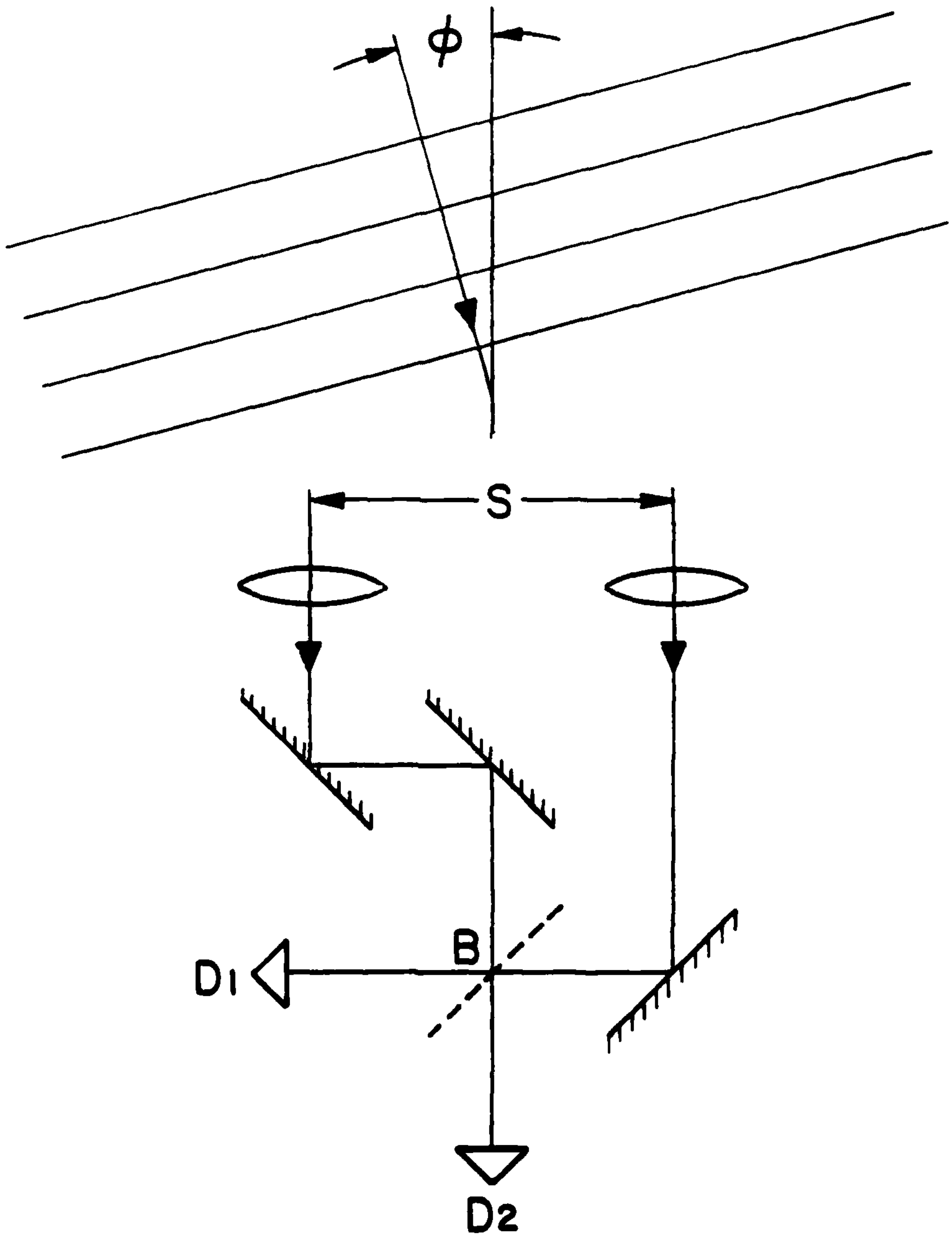


Figure 6 - Principle of Background Intensity Compensator

addition, the use of a narrow band source eliminates the need for an achromatic phase shift between the two beams.

3.2.1. Optical Layout

Figure 7 schematically illustrates the arrangement of the test equipment. The two lasers used are 3 mW He-Ne lasers. A point source is simulated by projecting the beam from laser L1 through a pinhole, thereby creating a Gaussian beam at the location of the compensator. The distance between the compensator and this pinhole was roughly 10 feet for all tests performed. Portions of this beam are separated by mirror M1 and prism 1 and mixed in the beamsplitter, B. The separation of the two beams is adjusted by translating M1 along the x-direction. Prism 1 can be moved in the y-direction to roughly balance the path lengths of the separate legs. In order to introduce small changes in the relative phase of the two beams easily, a piezoelectric "inchworm"[1] was mounted to translate prism 2 in the y-direction.

After mixing the beams in the beamsplitter, they were focused onto the two detectors D1 and D2. Note that the objectives are on the detector sides of the beamsplitter. The specifications for these lenses are greatly simplified by placing them in the combined wavefronts. The signals detected by D1 and D2 were then amplified and subtracted in a difference amplifier. The difference output due to the signal source alone was maximized to align the two beams properly. The optical elements used had a typical surface quality of $\lambda/10$, and the phase variation of the optimally aligned wavefronts over the selected apertures was less than $\lambda/4$. Alignment of the apparatus was accomplished by rotating M2 and M3. Both mirrors could be rotated about two axes, one parallel and the other perpendicular to the horizontal plane.

Light from the second laser, L2, was expanded and directed onto a window coated with particulate scattering material. This simulated background source could be positioned at any location between the signal source and the interferometer structure. An irregular background was created by applying the particles to the window in streaks. The background could be made even less uniform, both spatially and directionally, by aiming the specular reflection from the window into one or both legs of the interferometer.

3.2.2. Test Results

Several system configurations, using different beam separations, apertures and background characteristics, were tested. Results for all of the configurations were similar in that the intensity due to background sources could be substantially subtracted from the desired point-like signal intensity.

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[1]Inchworm Translators are a product of Burleigh Instruments, Fisher, New York.

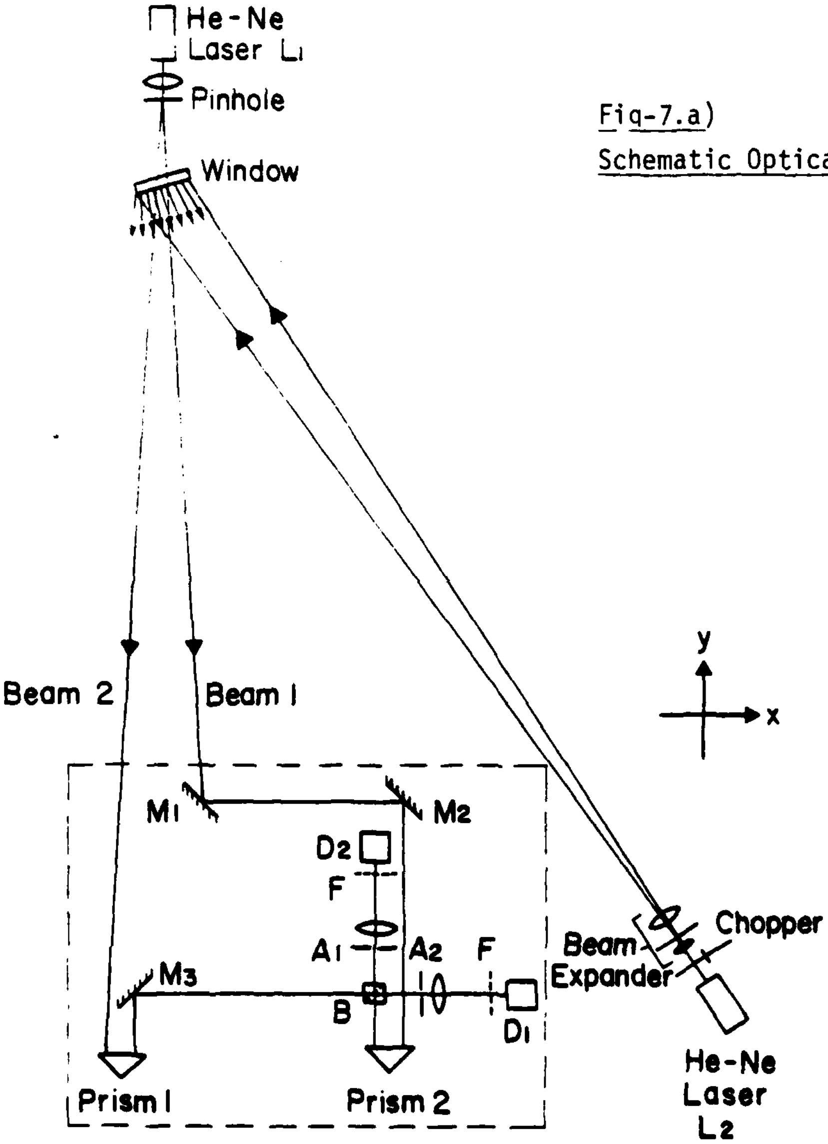
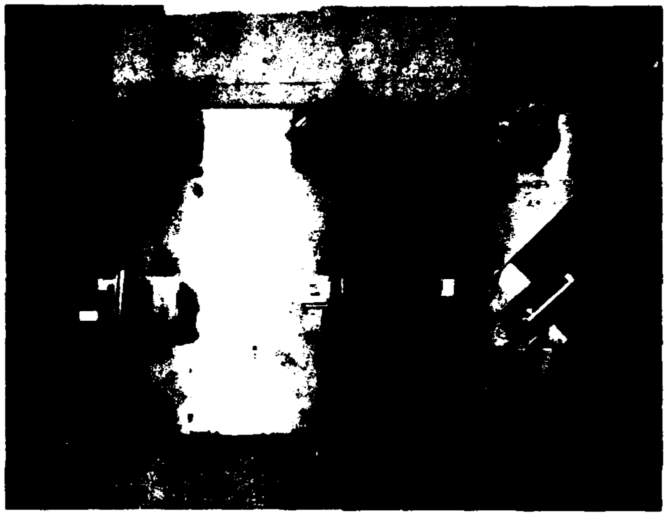


Fig-7.a)
Schematic Optical Lay-Out

Figure 7 - Testing of Background Intensity Compensator

Fig-7.b) - Photograph of Dashed Box in Fig-7.a



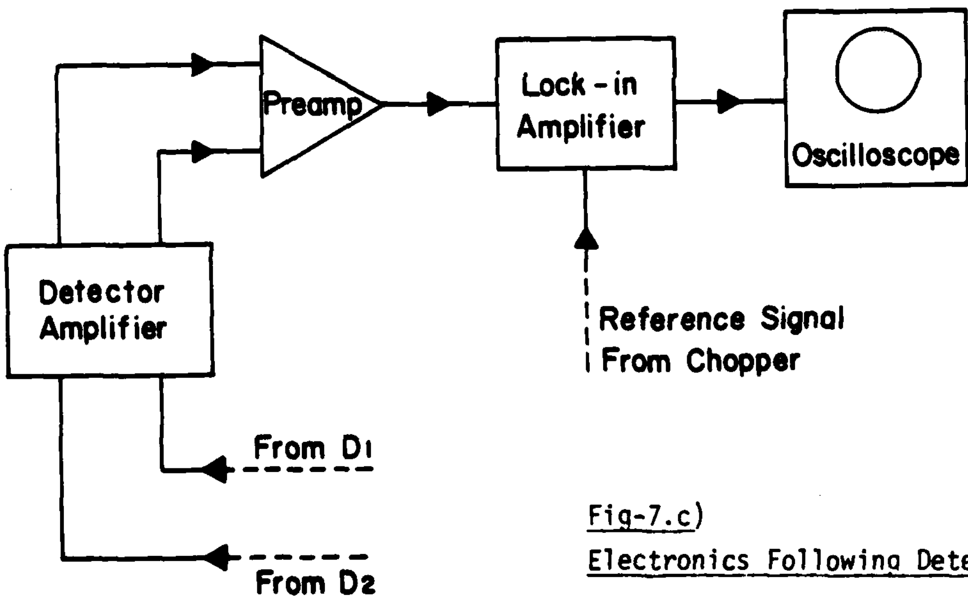


Fig-7.c)
Electronics Following Detectors

Figure 7 - (continued)

The magnitude of the difference output from the two detectors is a maximum for the signal source when the relative phase difference between the two beams is 0° or 180°. Since no means were provided to maintain this optimal phasing actively, the difference output would shift due to vibrations and temperature variations. For this reason, values of the difference output were measured by driving the inchworm while monitoring the peak-to-peak signal voltage on an oscilloscope. The balance between the detectors was then adjusted by centering this oscillating difference output about 0 V.

Table I summarizes the results of measurements made with both the background and signal sources in operation. The distance from the window, which was used to simulate the background source, to the front of the compensator is labeled here as W. The dimensions of the rectangular apertures which define the extent of the beams are given in the column labeled Ap. The separation between the two beam centers is labeled d. The background to signal intensity ratio was measured by blocking one beam and monitoring a single detector output while turning on the background and signal sources separately; this output was insensitive to the phasing of the two beams. The ratio was varied by attenuating the signal or the background or by changing the properties of the background. The other intensities in the table are peak-to-peak values of the difference output. Since it is only necessary to compare intensities within the table, arbitrary units are used. For most cases, the signal level changed only slightly when the background source was turned on and off. In order to increase the magnitude of the background relative to the signal, several measurements were made with the specular reflection from the scatter window entering one or both beams. Note that this caused the background to become extremely nonuniform. The peak-to-peak difference output in this case was comparable to the values obtained in the nonspecular reflection source of background. The decision was made to retain the original window, however, because the other windows produced larger wavefront aberrations in the signal source.

It should be mentioned that the balance of the two detectors was adjusted for each set of measurements. This was required since the beamsplitter had a dividing ratio of ~ 45/55 as opposed to the ideal 50/50. If the background intensity level of one beam is different from the other, the unbalanced splitting channels more light into one of the detectors. This effect could therefore be reduced either by improving the beamsplitter or by applying the system only to backgrounds with equal intensity in the beams. Alternatively, the balance could be actively adjusted to minimize the background level.

The noise sources arising in the electronics contributed an apparent intensity in the difference output of 0.06 ± 0.01 (see Table I), causing the measurements of the nonspecular background intensity to be systematically too large. In order to determine more accurately the reduction of the background source, a chopping system was introduced. The laser for the background source was placed behind a chopper-wheel, with an encoder on the wheel serving as a reference signal for a lock-in amplifier. This technique greatly increased the dynamic range of the measurements of the difference output. Table II compares the background level due to a single detector output with that due to the difference output

Table I - Background Intensity Compensator Test Results

				Difference Mode Measurements (1)		
w (in)	d (in)	Ap (in x in)	background / signal	signal on background on	signal on background off	signal off background on
18	0.79	0.160 X 0.320	5.76	28.7	19.2	10.7 (2)
			54.2	14.1	2.87	12.0 (2)
			1.04	18.2	16.3	2.86 (2)
			1.88	14.4	11.0	2.87 (2)
106	2.02	0.240 X 0.254	0.94	1.86	1.86	0.06 (4)
			3.33	0.25	0.25	0.06 (4)
			7.50	0.11	0.11	0.06 (4)
106	0.59	0.240 X 0.254	1.77	1.04	1.04	0.06 (4)
			5.43	0.25	0.25	0.06 (4)
			6.79	0.15	0.15	0.06 (4)
106	0.59	0.082 X 0.320	1.18	0.58	0.58	0.06 (4)
			1.25	0.39	0.39	0.06 (4)
			6.67	0.09	0.09	0.06 (4)
			4.92	20.1	19.2	2.39 (3)

(1) - Typical measurement uncertainty of $\pm 3\%$ (except where one significant digit is shown)

(2) - Specular reflection entering both beams

(3) - Specular reflection entering beam 1 only

(4) - No specular reflection in beams (these values did not change noticeably when the background was turned off)

Table II - Background Intensity Compensator Test Results

Background	Lock-In Amplifier Output: Single Detector On	Lock-In Amplifier Output: Difference Mode	Reduction Factor
Specular reflection in beam 1 only	102	0.20	510
Specular reflection in beam 2 only	192	0.25	770
Diffuse scattering (specular reflection off)	1.12	0.0050	220
" "	0.66	-0.0025	260

Beam separation = 0.59"

Aperture shape = 0.082" X 0.320"

for several cases. It was found that, after adjusting the balance of the detectors, the background was typically reduced by a factor of several hundred while operating in the subtractive mode. The primary limitations on further reduction were simply the "graininess" of the balance potentiometer and random fluctuations of the lock-in amplifier output.

3.3. Applications

There already exist various methods for correcting a signal contaminated by background radiation. These methods are based upon interpolation of the background superimposed on the source through measurements of the background in regions near the source. For a single detector system, this technique requires some type of scanning device. This can significantly reduce the time available to measure the signal, especially when rapid changes in the background are occurring. Alternatively, a multi-detector system can be used in order to continually monitor the signal and surrounding background.

In using the method of background subtraction described here, one must considerably increase the complexity of the optical design over the conventional designs. The new design offers two primary features which, in some cases, may justify the added complexity. One advantage is the elimination of the hardware and processing required to estimate the background at the source from the surrounding background. The other advantage is quite unique to this design and relies on the spatial separation of the input beams. If the two beams corresponding to a background source do not overlap on the detector, no interference between the beams can occur. In this case, the background source can be arbitrarily nonuniform and the resulting detected intensities will be subtracted to the precision set by the quality of the beamsplitter.

The greatest limitation imposed on this design is the requirement for a point-like signal source. Nevertheless, several useful applications exist for a device such as this. Radar systems which operate in the presence of a nonuniform background (such as varying weather conditions) could benefit by this technique. Microwave and radio communication could be made less susceptible to interfering (or jamming) backgrounds. Note also that the power requirements of the source or the receiving aperture area could be reduced with sufficient subtraction of the background sources.

It is also possible that the principle would aid in detection or communication in the visible and infrared portions of the spectrum. In this case, careful consideration would be required of the effects of atmospheric turbulence on the signal detectability. None of the tests performed have addressed this problem. However, it is likely that active alignment techniques could compensate for such fluctuations if the individual apertures were small in comparison to the dominant scale length of wavefront aberrations introduced by turbulence.

4. Concluding Remarks

It is clear that the most significant conclusion arising from this study is the inability of the initially proposed instrument to increase the detected signal to background ratio. An extensive search has been conducted for other types of instruments capable of detecting signal photons preferentially over background photons; this search has been, to date, unsuccessful.

Although the initially proposed instrument was found not to be practicable, this result does represent newly acquired knowledge which may be useful in other studies. In addition, significant progress has been made on the background intensity compensator. The potential applications of this device are much more limited than those of the initial instrument; however, this study has demonstrated that the background intensity compensator, within the specified constraints, will function in the manner intended.

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